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<p>This report acknowledges funding for the VI. van der Ziel Symposium on Quantum 1/f Noise and Other Low Frequency Fluctuations in Electronic Devices, which was organized by the author at the University of Missouri - St. Louis, on May 27-28, 1994. Like the previous symposia organized by us in October 1985, October 1986, April 1988, May 1990 and May 1992, this event brought together 24 researchers from universities, industrial and governmental research laboratories, and the industry, working in the field of Quantum 1/f Noise and other low frequency fluctuations in high - technology devices. A total of 21 papers was presented, including 6 invited papers. They mark important progress in the field, both in theory and experiment. The proceedings are still in print, and 6 copies will be appended as soon as they come out.</p>			
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# FINAL TECHNICAL REPORT

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NOISE AND OTHER LOW FREQUENCY FLUCTUATIONS IN

ELECTRONIC DEVICES

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## ABSTRACT

This report acknowledges funding for the VI. Symposium on Quantum  $1/f$  Noise and Other Low Frequency Fluctuations in Electronic Devices, which was organized by the author at the University of Missouri - St. Louis, on May 27-28, 1994. Like the previous symposia organized by us in October 1985, October 1986, April 1988, May 1990 and May 1992, this event brought together 24 researchers from universities, industrial and governmental research laboratories, and the industry, working in the field of Quantum  $1/f$  Noise and other low frequency fluctuations in high - technology devices. A total of 21 papers was presented, including 6 invited papers. They mark important progress in the field, both in theory and experiment. To explain the subject of this Symposium, this report focuses on the description of the present state and of the research directions in the field of Quantum  $1/f$  Noise, although other low frequency fluctuations were also included (as in the past), in order to widen the scope of the Symposium and the pool of participants. The report also presents a scientific overview of the papers presented, a list of papers, a list of attendees, and a list of participants. The proceedings are still in print at the American Institute of Physics, and will be appended to this report as soon as they come out.

In most high-technology applications  $1/f$  noise appears as a low-frequency fluctuation or slow drift of the device parameters, which limits the achievable performance and stability. On the other hand, physical cross sections and process rates have been shown theoretically by the author to fluctuate with a  $1/f$  spectral density according to a simple universal formula. This new formula gives the power spectrum of cross section fluctuations if the velocity change of the scattered current carriers in the process is known. We can now calculate quantum  $1/f$  noise in all forms of scattering (impurity, phonon, umklapp, inter-valley), in bulk and surface recombination and tunneling rates, as well as emission processes. A very successful unified description of  $1/f$  noise in electronic devices has thus been constructed with the help of vitally important AFOSR funding in an earlier phase (Grants AFOSR-84-0229 and 89-0416). The unified description and the quantum  $1/f$  noise formula have been verified in many systems, such as vacuum tubes, secondary emission tubes, semiconductors, pn junctions, semiconductor devices, in particular infrared detectors, transistors, submicron devices, etc.. The quantum  $1/f$  theory was used with success to reduce  $1/f$  noise in infrared detectors, various transistors, and ultrasmall electronic devices. It was also applied with success to Josephson junctions and SQUID's, quartz resonators, laser gyroscopes, and radioactive decay. Nevertheless, most electronic and electro-optic devices, including the ultrasmall devices, are still operating considerably above the theoretical limit set by the quantum  $1/f$  noise theory. Therefore, the main objective of the participants at the present Symposium was to cooperate in this new field, in order to further reduce the  $1/f$  noise in the known devices, and to extend the application to new devices which are now being developed, including new FETs with ultralow gate leakage currents, new infrared detectors, new compact frequency standards, and high  $T_c$  superconductors. The focus of the Symposium also included further development of the quantum  $1/f$  theory, and its connection to studies of quantum and classical deterministic chaos in the intermediary region between conventional and coherent quantum  $1/f$  effects. Finally, this Symposium benefited those involved in virtually all high-tech applications, through general low  $1/f$  noise design and optimization principles, as well as through an improved understanding of the quantum  $1/f$  effect as a technically important fundamental law of nature. Past Symposia were funded by ARO (I-III), ONR (IV) and NSF (V).

We are most thankful to AFOSR for the support of this Symposium.

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## I. INTRODUCTION

The present report on the "Fifth van der Ziel Symposium on Quantum  $1/f$  Noise and Other Low Frequency Fluctuations in Electronic Devices" which was held at the University of Missouri, St. Louis, MO, on May 27 and 28, 1994, brings a brief presentation of the main subjects discussed in the papers presented, a list of attendees, a list of papers, and a list of authors. The Symposium was organized by P. H. Handel with the help of A. L. Chung, similar to the previous five symposia. Like the previous ones, the present symposium was again successful in bringing together scientists and students from universities and industrial, as well as governmental, research and development laboratories working in this new field of tremendous practical and theoretical importance, vital for most high-technology applications. To describe the importance of this new field and to explain its relevance for high-tech applications, we provide in this introduction a review of recent developments and a few examples of quantum  $1/f$  theory applications.

During the last four years we have achieved considerable progress in the field of Infra Quantum Physics which includes the conventional and coherent state quantum  $1/f$  effects. The progress included both theory and experiment. **On the theory front**, a more rigorous derivation of the fundamental quantum  $1/f$  effect formula in the language of second quantization was developed, and the pair-correlation function was calculated in the general case of  $N$  particles present in the final state. Progress in theory also included a calculation of the quantum  $1/f$  cross-correlation spectra, the derivation of the effect of a finite mean free path, and a detailed calculation, with the collaboration of G. Kousik and C.M. Van Vliet, of mobility fluctuation spectra predicted by the theory. **On the experimental front**, with the collaboration of A. van der Ziel, C. Jones, W. Radford, G. Bosman, E. Kelso, Q. Peng, C.M. Van Vliet, A. van Rheenen, D. Wolf, T. Musha, and of many talented graduate students, the theory was both verified and successfully applied to many systems. The most important applications included junction-type and MIS-type infrared detectors, HEMTs, PBTs, BJTs, HBJTs, JFETs, and SQUIDs. The theory was also verified quantitatively in vacuum tubes, secondary emission tubes, photomultipliers, thin semiconducting and metallic sheets, as well as qualitatively in quartz resonators, SAW devices, piezoelectric and ferroelectric materials, in nuclear  $\alpha$ -decay and in  $\beta$ -decay. With the help of measures suggested on the basis of the simple quantum  $1/f$  effect formula, high-technology industrial laboratories were able to reduce the  $1/f$  noise level of infrared detectors by two orders of magnitude. The hopeless uncertainty and ignorance which handicapped device builders in the past when it came to understanding, theoretically predicting and controlling  $1/f$  noise has become a thing of the past. There is, however, no smooth transition between the conventional quantum  $1/f$  effect theory and the coherent state quantum

1/f theory; all we have to connect these two important special cases is a heuristic interpolation formula which I suggested in 1985 on qualitative physical grounds. Furthermore, although we had a spectacular noise reduction of two orders of magnitude during the last four years in junction-type infrared detectors, most high-technology devices still operate at 1/f noise levels which considerably exceed the quantum limit given by my formula for ideal conditions. Finally, some new devices, in particular those with layered structures and those utilizing high T superconductors, have not yet been analyzed on the basis of the quantum 1/f theory, and are unnecessarily handicapped by 1/f noise. These three examples suggest and illustrate the **three main challenges** we face today: 1) Further improvement of the most important high-technology devices vital for our technology edge, and which have already been improved considerably in the past grant period on the basis of the quantum 1/f theory; 2) Application of the fundamental quantum 1/f formula to new devices, in particular to those newly developed devices, important for high-performance leading edge instrumentation, which exhibit degrading noise, parameter drift, or instability problems. Examples of such new devices are the high T<sub>c</sub> superconducting infrared detectors and the layered devices. We hope to improve the new devices considerably by using the quantum 1/f formula. A secondary result will be further critical verification and scrutiny of the quantum 1/f theory, and growth in our experience, as well as in the ability of high-technology industries to control 1/f noise; 3) Further development of the quantum 1/f theory.

Sec. II describes the papers presented, Sec. III is a list of attendees, Sec. IV is a list of papers and Sec. V brings a list of authors.

## II. SUMMARY OF THE SCIENTIFIC PAPERS PRESENTED AT THE SYMPOSIUM

Papers presented at the Symposium addressed quantum 1/f theory aspects (Widom, Handel, Zhang), 1/f noise in new materials (Tacano, Dagge et al.), general 1/f noise problematics (Van Vliet and Huisso), and 1/f noise in devices (Lukyanchikova, Koslowsky, Simoen) including ultrasmall devices (Kochelap), and VLSI circuits (Celic-Butler).

The quantum 1/f noise theory papers have addressed the relation between 1/f noise and quantum chaos, showing that quantum 1/f noise is a form of quantum chaos. Quantum mechanics itself represents chaos at a more fundamental level. Other quantum 1/f theory paper focused on the connection between coherent and conventional quantum 1/f noise, extending a bridge from the coherent side in the conventional direction.

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#### IV. LIST OF PAPERS PRESENTED

**Quantum " $1/\omega$ " Noise and Space-Like Photon  
Propagation (Invited)**

A. Widom, Y.N. Srivastava and E. Sassaroli

**SQUID Rings as Macroscopic Quantum Objects: The  
Quantum-Classical Interface (Invited)**

R.J. Prance, R. Whiteman, H. Prance, T.D. Clark, J. Diggins,  
J.F. Ralph, T.P. Spiller, A. Clippingdale, A. Widom and  
Y. Srivastava

**New Noise Problems in an Old Form: "Recycling" Fluctuation  
Phenomena (Invited)**

C.M. Van Vliet and A. Huisso

**G-R Noise in GaAs/Al<sub>0.4</sub>Ga<sub>0.6</sub>As Resonant Tunneling  
Diodes (Invited)**

C. Surya

**$1/f$ -Noise in Thin Aluminum Films Damaged by  
Electromigration**

K. Dagge, J. Briggmann, C. Reuter, A. Seeger and H. Stoll

**Impact of the Substrate Quality on the Low Frequency Noise of Silicon Diodes**

E. Simoen, G. Bosman, J. Vanhellemont and C. Claeys

**1/f Noise in Scanning Tunneling Microscopy**

B. Koslowski

**Simulation of Heat Transfer Effects Upon HBT Noise Spectra**

J. Anderson

**Strong Low-Frequency Noise in Buried-Channel pMOSFETs Under Inversion Conditions**

N. Lukyanchikova, M. Petrichuk, N. Garbar, E. Simoen and C. Claeys

**1/f Noise in Metallic Thin Films (Invited)**

J. Sikula, P. Schauer, P. Vasina, M. Sikulova, B. Koktavy, Z. Chobola, H. Navarova and L. Pazdera

**Limitation and Suppression of Electron Noise in Sub-micrometer Semiconductor Structures (Invited)**

V.A. Kochelap, V.N. Sokolov, N.A. Zakhleniuk and O.M. Bulashenko

**Shot Noise Addition in Parallel Mesoscopic Constrictions**

M. Macucci

**Aging and Noise in the Si Bipolar Junction Transistor**

A. Mounib, G. Ghibaudo, D. Pogany and J.A. Chroboczek

**Chaos Generated Noise in Radio Frequency SQUID Magnetometers**

J. Diggins, J.F. Ralph, T.P. Spiller, T.D. Clark, H. Prance, R.J. Prance and F. Brouers

**Nonlinear Effects in the 1/f Noise of Lattice-Matched InAlAs/InGaAs HEMT's**

M. Mihaila, C. Heedt and F.J. Tegude

**Detection of Via Electromigration in VLSI Circuit Metallizations by 1/f Noise Measurements**

R. Zhang and Z. Çelik-Butler

**Growth of InAlAs/InGaAs Heterostructure and its 1/f Noise Characteristics (Invited)**

M. Tacano

**The Physical Meaning of the Quantum 1/f Effect as a Form of Quantum Chaos**

P. H. Handel

**A Bridge between Coherent and Conventional Quantum 1/f Noise**

P.H. Handel and Y. Zhang

**Discussion of the 1987 Conventional Quantum  $1/f$  Noise  
Source Term**

P.H. Handel

**$1/f$  Noise in Fluid Films**

S. Cable and T. Tajima (presented at the XII. International

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